



Review

Influence of Cu on the catalytic activity of FeBEA zeolites in SCR of NO with NH₃Paweł Boroń ^{a,b,c}, Lucjan Chmielarz ^{a,***}, Stanisław Dzwigaj ^{b,c,*}^a Faculty of Chemistry, Jagiellonian University, Ingardena 3, 30-060 Kraków, Poland^b Sorbonne Universités, UPMC Univ Paris 06, UMR 7197, Laboratoire de Réactivité de Surface, F-75005 Paris, France^c CNRS, UMR 7197, Laboratoire de Réactivité de Surface, F-75005 Paris, France

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ABSTRACT

Two series of Fe and/or Cu containing BEA zeolites were prepared by different procedures: two-step post-synthesis method (Fe_xSiBEA , Cu_xSiBEA and $\text{Fe}_x\text{Cu}_x\text{SiBEA}$) and conventional wet impregnation ($\text{Fe}_x\text{HAI}BEA$, $\text{Cu}_x\text{HAI}BEA$ and $\text{Fe}_x\text{Cu}_x\text{HAI}BEA$) ($x = 1.0$ Fe or Cu wt%). Modification of BEA zeolite resulted in the incorporation of iron and/or copper into vacant T-atom sites of the zeolite framework as evidenced by XRD and DR UV-vis. Transition metals (Cu or Fe) were incorporated into the framework of BEA zeolite as pseudo-tetrahedral Fe (III) or Cu (II) as proved by XRD, DR UV-vis and TPR investigations. All of obtained zeolite materials were found to be active catalysts of selective catalytic reduction of NO with ammonia. Analysis of NO conversion and catalyst reducibility indicated that the latter played an important role in the DeNO_x process. Co-presence of copper in the zeolite structure decreased the reducibility of iron in $\text{Fe}_x\text{Cu}_x\text{SiBEA}$ and $\text{Fe}_x\text{Cu}_x\text{HAI}BEA$, and had significant influence on the low temperature NO conversion.

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1. Introduction

Worldwide environmental regulations regarding NO_x emissions from diesel engines have become significantly more stringent

leading to innovative applications of new technologies to resolve this environmental problem. As a potent technology, the selective catalytic reduction (SCR) of NO has been studied intensively [1–4]. Iron and copper based zeolite catalysts are widely employed in selective catalytic reduction of NO with ammonia due to their high temperature durability compared to vanadium based catalysts [5].

Hence, the focus has shifted to the Fe- and Cu-based zeolite catalysts, both of which have demonstrated very high NO reduction efficiencies at high space velocities. The Cu-based catalysts are

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particularly effective at lower temperatures (<620 K) [6,7]. Moreover, NO removal efficiencies over the Cu-based catalysts are found to be rather insensitive of the amount of NO₂ in the feed at lower temperatures [7]. On the other hand, the Fe-based catalysts are active at higher temperatures (>620 K) and give very high NO reduction efficiencies even at very high temperatures (up to 870–970 K) [8,9]. Given the differences in activities of the Cu- and Fe-based catalysts, it seems plausible that a combination of the Fe-zeolite and Cu-zeolite catalysts might achieve high NO conversions over a broader temperature range than the individual catalysts.

A few literature studies considered such combined Fe- and Cu-zeolite systems [10–13]. Metkar and co-worker [10,11] studied the combined Fe- and Cu-zeolite monolithic catalysts. The Fe/Cu dual layer catalyst exhibited superior performance for the SCR reaction. Krocher and Elsener [12], who studied double bed catalytic reactors for the SCR reaction, have found that a Fe-zeolite section followed by a Cu-zeolite bed gives higher NO conversion efficiencies. Girard et al. [13] carried out similar studies on combinations of Fe- and Cu-zeolite monolith. They found that the series combinations of (33%) Fe-zeolite followed by (67%) Cu-zeolite gives the highest NO reduction efficiency throughout the studied temperature range. Similar studies on the series of the Fe and Cu-zeolite catalysts with different individual catalyst lengths were carried out by Theis and McCabe [14]. The approach of the combining of two or more distinct catalysts to achieve the improved performance has been considered in the other reaction systems [15][e.g. 15]. The other studies [16][e.g. 16] reported the use of the so-called dual layer monolithic catalysts for SCR of NO with hydrocarbons (e.g. propene) as reducing agents.

Even though the previous studies showed improvements in NO conversion over the Cu and Fe co-exchanged catalysts [10–16], the effect of the preparation method and state of transition metal present in the zeolite structure is not well documented. Usually, transition metal ions are introduced in the extra-framework position of the zeolite structure by ion exchange method. The objective of the earlier studies [10–16] was to determine if the dual-layer Fe/Cu zeolite catalysts can exhibit improved performance for lean NO reduction. Examination of various combinations of the sequential brick and dual layer catalysts was deeply investigated [10,11]. The general aim of the earlier studies [10,11,16] was to systematically vary the lengths of the Fe- and Cu-zeolite monoliths in order to identify superior axial configurations, along the lines of the pioneering studies of Ford Motor Company [17].

Unfortunately, there are only few recent reports that have been focused on the single layer Fe/Cu-catalysts in SCR-NO using NH₃ as a reducing agent. It is worth to note that zeolite containing simultaneously two metal cations was attempted for broadening of the NO conversion temperature window [10,11]. Even though, the previous studies showed improvements in NO conversion over the Cu and Fe co-exchanged catalyst, the effect of variation of Cu/Fe ratio and preparation method is still not well documented.

Thus, in contrast to the previous studies [10,11,16][e.g. 10,11,16], in which the dual layer catalysts were thoroughly investigated, our approach is to obtain single zeolite containing simultaneously two metal cations (Cu and Fe) by two-step postsynthesis and conventional wet impregnation procedures. As it was earlier shown [18,19] for iron and copper, it is possible to control the incorporation of Fe or Cu into the framework of BEA zeolite using the two-step postsynthesis method. The catalytic activities of FeCuSiBEA and FeCuHAIPEA in SCR-NO with ammonia were compared with the single metal (Fe or Cu) catalysts. The speciation of transition metals in FeCuSiBEA and FeCuHAIPEA zeolites was determined in order to evidence a "structure-properties" relationship in the selective catalytic reduction of NO with NH₃.

2. Experimental

2.1. Materials

Two series of Cu and/or Fe-containing zeolites were prepared by two-step postsynthesis and conventional wet impregnation procedures. Fe_xSiBEA, Cu_xSiBEA and Fe_xCu_xSiBEA zeolites (where x = 1.0 wt% of Fe or Cu, respectively) were prepared by the two-step postsynthesis procedure reported earlier [18,19]. In the first step, 2 g of HAIPEA zeolite, obtained by calcination in air at 823 K for 15 h of tetraethylammonium form of BEA (TEABEA) zeolite (Si/Al = 12.5), provided by RIPP (China) was treated with 13 mol L⁻¹ HNO₃ solution under stirring (4 h, 353 K) to remove aluminium from the zeolite structure. In the second step, 2 g of resulting SiBEA (Si/Al = 1000) obtained after filtration were dispersed in aqueous solutions (pH 2.5) containing 1.8 × 10⁻³ mol L⁻¹ of Fe(NO₃)₃·9H₂O and/or 1.5 × 10⁻³ mol L⁻¹ of Cu(NO₃)₂·3H₂O and stirred at room temperature for 24 h. Then, the obtained suspensions were stirred in evaporator under vacuum of a water pump in air at 353 K for 2 h until water was evaporated. The solids with the iron or copper content of 1.0 wt% were labelled as Fe_{1.0}SiBEA, Cu_{1.0}SiBEA and Fe_{1.0}Cu_{1.0}SiBEA, respectively.

Fe_xHAIPEA, Cu_xHAIPEA and Fe_xCu_xHAIPEA zeolites (where x = 1.0 wt% of Fe or Cu, respectively) were prepared by conventional wet impregnation method. Firstly, NH₄AlBEA was calcined in air at 773 K for 3 h to obtain the acidic form of BEA zeolite (HAIPEA). Secondly, 2 g of HAIPEA were dispersed in aqueous solutions (pH 3.0) containing 1.8 × 10⁻³ mol L⁻¹ of Fe(NO₃)₃·9H₂O and/or 1.5 × 10⁻³ mol L⁻¹ of Cu(NO₃)₂·3H₂O and stirred at room temperature for 24 h. Then, the suspensions were stirred in evaporator under vacuum of a water pump in air at 353 K for 2 h until water was evaporated. The solids with iron or copper content of 1.0 wt% were labelled as Fe_{1.0}HAIPEA, Cu_{1.0}HAIPEA and Fe_{1.0}Cu_{1.0}HAIPEA, respectively.

2.2. Techniques

The structure of the studied samples was determined by powder X-ray diffraction. Diffraction patterns were obtained by a PW 3710 Philips X'pert (Philips X'pert APD) diffractometer using Ni-filtered Cu K α radiation ($\lambda = 1.54056 \text{ \AA}$). The measurements were performed in the range of 2 θ from 5 to 50° with a 0.02° step.

Textural properties of the samples were determined by adsorption of nitrogen at 77 K using a Micromeritics ASAP 2010 apparatus. Prior to nitrogen adsorption all the samples were outgassed, first at room temperature and then at 623 K. The specific surface areas were determined from nitrogen adsorption isotherms in the relative pressure (P/P₀) ranging from 0.05 to 0.16 using BET method, while the micropore volume was determined from the P/P₀ below 0.2.

The DR UV-vis spectra were recorded using an Evolution 600 (Thermo) spectrophotometer. The measurements were performed in the range of 200–800 nm with a resolution of 2 nm. DR UV-vis spectroscopy was applied to determine chemical nature of iron and/or copper species in the zeolite structure.

Hydrogen temperature-programmed reduction (TPR) was carried out in a flow of 5% of H₂ in Ar (25 mL min⁻¹). The sample was placed in a quartz microreactor and the quantitative consumption of H₂ from 300 to 1120 K (7.5 K min⁻¹) was monitored by a TCD detector.

2.3. Catalytic tests

Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA, Fe_{1.0}HAIPEA, Cu_{1.0}HAIPEA and Fe_{1.0}Cu_{1.0}HAIPEA were studied as catalysts for SCR of NO with ammonia. Catalytic experiments were performed in a fixed-bed flow microreactor system. The reactant

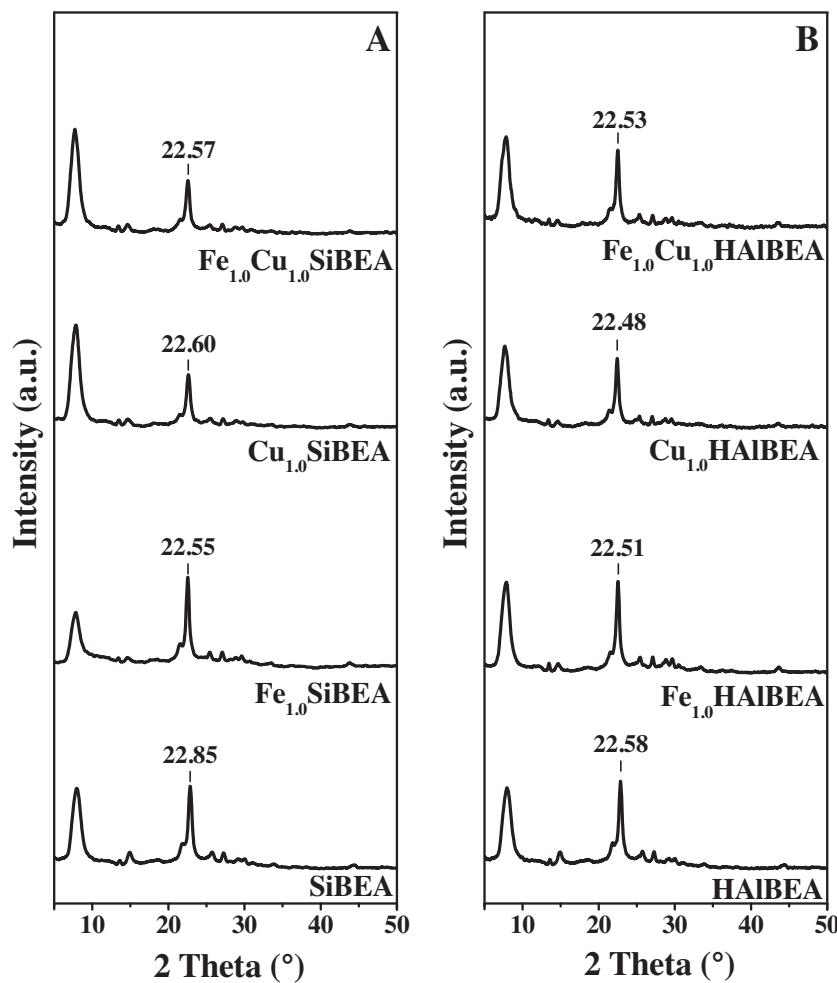


Fig. 1. XRD patterns recorded at room temperature of SiBEA, Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA (A), and HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA, Fe_{1.0}Cu_{1.0}HAIBEA (B).

concentrations were continuously measured using a quadrupole mass spectrometer RGA 200 Prevac, with Faraday cup (FC) detector, connected directly to the reactor outlet. Sensitivity of the detector is equal 2×10^{-4} A Torr⁻¹ (measured with N₂ 28 amu with 1 amu full peak width 10% height, 70 eV electron energy, 12 eV ion energy and 1 mA electron emission current). The minimum detectable partial pressure is about 5×10^{-11} Torr. Prior to the reaction, each sample (100 mg) of the catalyst was outgassed in a flow of pure helium at 823 K for 30 min. The following composition of the gas mixture was used: [NO] = [NH₃] = 0.25 vol.%, [O₂] = 2.5 vol.% and [He] = 97 vol.%. The reaction was studied in the temperature range between 373 K and 823 K. Total flow rate of the reaction mixture was 40 mL min⁻¹, with a weight hourly space velocity (WHSV) of about 24,000 mL h⁻¹ g⁻¹.

3. Results and discussion

3.1. Introduction of iron and copper into BEA zeolite

3.1.1. X-ray diffraction

Fig. 1A and B presents X-ray diffraction patterns of SiBEA, Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA (Fig. 1A), HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA and Fe_{1.0}Cu_{1.0}HAIBEA (Fig. 1B). The XRD patterns of all the samples are similar and characteristic of BEA zeolite. The crystallinity is preserved after dealumination and the samples do not show any evidence of extra framework crystalline compounds or long-range amorphization of the zeolite structure, as reported earlier [20,21]. Similar XRD diffractograms

recorded for all the samples show that introduction of iron and/or copper ions into zeolites do not induce any significant changes in the BEA structure.

The absence of reflections characteristics of extra-framework iron and/or copper oxides in Fe_xSiBEA, Cu_xSiBEA and Fe_xCu_xSiBEA indicates a good dispersion of both Fe and Cu transition metals. It has been reported [22] that a narrow diffraction peak near 22–23° can be used to compare qualitatively lattice contraction/expansion of the BEA structure. An increase of the d_{302} spacing from 3.888 Å ($2\theta = 22.85^\circ$) for SiBEA to 3.939 Å ($2\theta = 22.55^\circ$) and 3.931 Å ($2\theta = 22.60^\circ$) for Cu_{1.0}SiBEA upon introduction of 1.0 wt% of Fe and Cu into SiBEA (Fig. 1A) indicates expansion of the matrix as a result of the reaction of iron or copper ions with OH groups of vacant T-atom sites (T=Si or Al) and their incorporation into the framework positions of BEA zeolite, as reported earlier [19–21,23]. In spite of this expansion, Fe_{1.0}SiBEA and Cu_{1.0}SiBEA exhibit similar intensity of diffraction lines as that observed for SiBEA, suggesting that incorporation of Fe and Cu ions into the zeolite framework does not affect their crystallinity. It should be noted that incorporation of both Fe and Cu into SiBEA zeolite results in an increase of the d_{302} spacing from 3.888 Å ($2\theta = 22.85^\circ$) for SiBEA to 3.936 Å ($2\theta = 22.57^\circ$) for Fe_{1.0}Cu_{1.0}SiBEA and also proves that iron and copper are incorporated into the BEA zeolite framework.

An introduction of 1.0 wt% of iron or copper into HAIBEA zeolite does not lead to such significant increase in the d_{302} spacing as it was observed upon incorporation of iron ions into SiBEA zeolite (Fig. 1B). In this case, a small increase in the d_{302} spacing from 3.934 Å ($2\theta = 22.58^\circ$) for HAIBEA to 3.946 Å ($2\theta = 22.51^\circ$) for

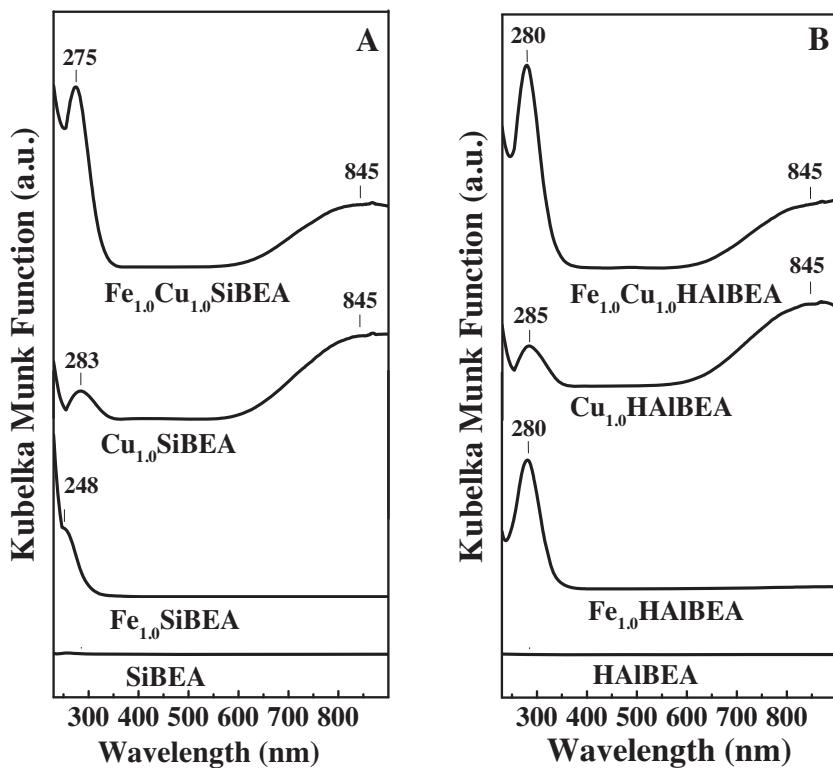


Fig. 2. DR UV-vis spectra recorded at ambient atmosphere of SiBEA, Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA (A), and HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA, Fe_{1.0}Cu_{1.0}HAIBEA (B).

Fe_{1.0}HAIBEA and 3.951 Å ($2\theta = 22.48^\circ$) for Cu_{1.0}HAIBEA, respectively (Fig. 1B) suggests that only some amounts of iron or copper have been incorporated into the framework of HAIBEA zeolite.

The incorporation of both iron and copper ions into HAIBEA zeolites leads also to a small increase in the interlayer distance in BEA matrix, what results in a shift of a narrow diffraction peak near 22–23° to lower values of 2 theta, from $2\theta = 22.58^\circ$ ($d_{302} = 3.934$ Å) for HAIBEA to $2\theta = 22.53^\circ$ ($d_{302} = 3.943$ Å) for Fe_{1.0}Cu_{1.0}HAIBEA (Fig. 1B). This effect is related to the reaction of iron and/or copper ions with OH groups of vacant T-atom sites and their partial incorporation into the framework positions of BEA zeolite.

Moreover, X-ray diffractogram recorded for each sample contains (302) reflection of similar intensity, suggesting that an introduction of Fe and/or Cu into zeolites does not affect their crystallinity.

It should be noted that all materials have similar high BET surface area (620–780 m² g⁻¹) and micropore volume (0.19–0.25 cm³ g⁻¹) characteristic for the BEA structure indicating that textural properties of BEA zeolite are preserved upon dealumination and introduction of iron or copper into BEA structure by two-step postsynthesis procedure as well as by conventional wet impregnation.

3.2. Nature and environment of iron and copper species in FeBEA, CuBEA and FeCuBEA zeolites

3.2.1. Diffuse reflectance UV-vis spectroscopy

The nature and environment of iron and copper present in obtained materials have been studied by DR UV-vis spectroscopy (Fig. 2). The white Fe_{1.0}SiBEA sample exhibits one band at 248 nm, assigned to oxygen-to-metal charge transfer (CT) transitions involving pseudo-tetrahedral Fe(III), what is in line with earlier results [24–29]. The absence of a broad band near 500 nm,

suggests that FeO_x oligomers are not present in Fe_{1.0}SiBEA [24–26]. The DR UV-vis spectra of Cu_{1.0}SiBEA are composed of a broad and intense band around 845 nm and another band at about 283 nm (Fig. 2A). These bands may be assigned to *d–d* Cu²⁺ (3d⁹) and charge transfer (CT) O^{2–} → Cu²⁺ transitions, respectively, of isolated Cu(II) in pseudo-tetrahedral coordination, taking into account earlier works on copper in different coordination, environment and crystal field [30–32]. The absence of DR UV-vis bands in the range 300–600 nm, assigned to O^{2–} → Cu²⁺ CT transition and/or *d–d* transition of octa-coordinated Cu(II) indicates that such copper species are probably not present in Cu_{1.0}SiBEA, in line with earlier works [33,34]. For Fe_{1.0}Cu_{1.0}SiBEA absorption bands at 275 and 845 nm can be assigned to pseudo-tetrahedral Fe(III) and Cu(II), respectively. It suggests that upon preparation of this sample by two-step postsynthesis method almost all Fe and Cu ions are incorporated in the SiBEA zeolite framework. Fig. 2B shows the DR UV-vis spectra recorded at room temperature for the HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA and Fe_{1.0}Cu_{1.0}HAIBEA samples. The Fe_{1.0}HAIBEA sample exhibits one band at 280 nm assigned to oxygen-to-metal charge transfer (CT) transitions involving pseudo-tetrahedral Fe(III) [24–26]. Moreover, for this sample a broad band near 400–550 nm is not observed what proves that extra-framework FeO_x oligomers and/or iron oxide are not present. It is in line with earlier studies [35,36]. The DR UV-vis spectrum of Cu_{1.0}HAIBEA is composed of a broad band around 845 nm and another less intensive band at 285 nm (Fig. 2B). These bands proves the presence of different kinds of mononuclear Cu(II) [30–32]. The absence of DR UV-vis band in the range 300–600 nm assigned to CT transition of binuclear [32,37] or trinuclear [33] copper–oxygen complexes suggests that such polynuclear complexes are probably not present in Cu_{1.0}HAIBEA. For Fe_{1.0}Cu_{1.0}HAIBEA, large bands at 280 and 845 nm are observed. These DR UV-vis results show that the catalyst with 1.0 wt% of iron and copper, contains mainly isolated pseudo-tetrahedral Fe(III) and Cu(II) in the framework of BEA zeolite.

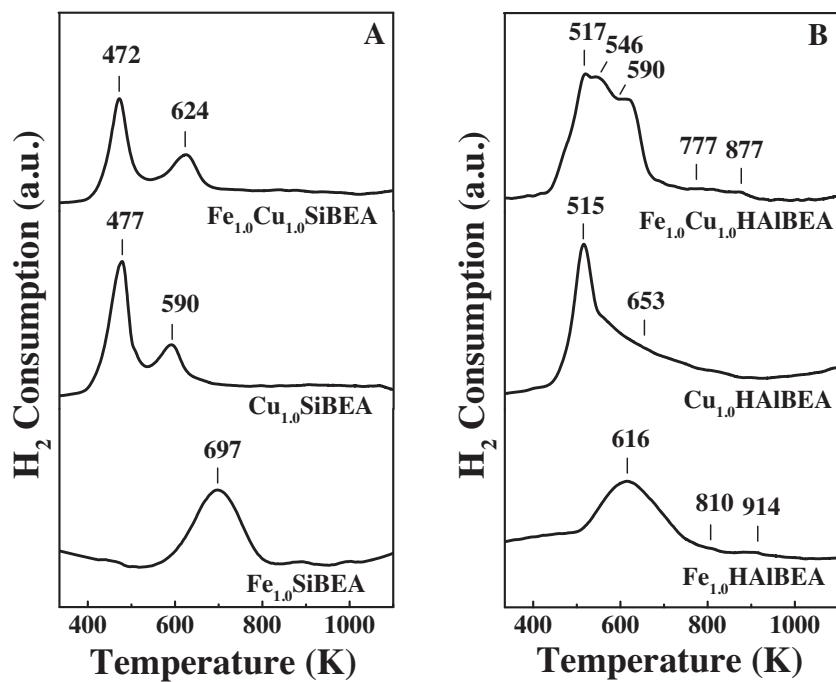


Fig. 3. H₂-TPR profiles of SiBEA, Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA (A), and HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA, Fe_{1.0}Cu_{1.0}HAIBEA (B).

3.2.2. Temperature-programmed reduction (TPR)

The reducibility of the Fe(III) and Cu(II) present in Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA (Fig. 3A), Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA and Fe_{1.0}Cu_{1.0}HAIBEA (Fig. 3B) has been investigated by temperature-programmed reduction (TPR) under flowing hydrogen (5 vol.% H₂ in Ar). Only one peak at 697 K, probably attributed to the reduction of framework pseudo-tetrahedral iron species from Fe(III) to Fe(II) oxidation state appears for Fe_{1.0}SiBEA (Fig. 3A), what is in line with earlier reports [38]. The TPR profile of Fe_{1.0}HAIBEA (Fig. 3B) shows two zones of hydrogen consumption: 513–753 K and >953 K. As it was reported in previous studies of Fe-ZSM-5 [39], Fe-Y [40] and Fe-BEA [41], the first peak of hydrogen consumption (at 616 K) would correspond to reduction of Fe³⁺ (bare Fe³⁺ cations, and oxo- or hydroxycations) into Fe²⁺. The high-temperature reduction peak (at 914 K) is ascribed to the reduction of Fe²⁺ to Fe⁰. H₂-TPR profiles of Cu_{1.0}SiBEA and Cu_{1.0}HAIBEA are given in Fig. 3A and B. Two reduction peaks at around 477 and 590 K are detected for Cu_{1.0}SiBEA, assigned to reduction of Cu²⁺ to Cu⁺ and Cu⁺ to Cu⁰ [42], respectively. While the Cu_{1.0}HAIBEA catalyst shows two reduction peaks around 515 and 653 K (Fig. 3B), that can be attributed to one step reduction of Cu²⁺ directly to Cu⁰ and reduction of Cu⁺ to Cu⁰ [42], respectively. Fe_{1.0}Cu_{1.0}SiBEA displays a very similar TPR profile as that recorded for Cu_{1.0}SiBEA, constituted by a good visible peak centered at ca. 472 K, which proves reduction of Cu²⁺ to Cu⁺. Moreover, the TPR profile of the catalyst, prepared by two-step postsynthesis

method, shows an additional small peak at 624 K corresponding to reduction of Cu⁺ to Cu⁰ and/or Fe³⁺ into Fe²⁺. In contrast three main and unresolved peaks at 517, 546 and 590 K, observed for Fe_{1.0}Cu_{1.0}HAIBEA prepared by wet impregnation procedure (Fig. 3B), could be attributed to reduction of Cu²⁺ directly to Cu⁰, framework tetrahedral Fe(III) to Fe(II) and Cu⁺ to Cu⁰, respectively, in line with earlier work [38,43]. The two additional TPR peaks appearing from 753 to 953 K could be attributed to the reduction of small clusters of Fe₃O₄ to FeO, and then FeO to Fe⁰, at ca. 777 and 877 K, respectively. The comparison of Fig 3A and B reveals that the presence of Cu along with Fe seems to decrease the reducibility of iron as seen from the TPR profiles of the Fe_{1.0}Cu_{1.0}SiBEA and Fe_{1.0}Cu_{1.0}HAIBEA catalysts.

It should be noted that the physicochemical properties (textural properties, nature of transition metals) determined for all the studied catalysts are collected in Table 1.

3.3. SCR of NO with NH₃

Fe and/or Cu containing BEA zeolites have been studied as catalysts for the selective reduction of NO with ammonia. Nitrogen and water vapour are desired products of this process, while N₂O is a side-product. The results of the studies performed for both series of the catalysts are presented in Figs 4 and 5. As it was earlier reported [18], dealuminated SiBEA shows a very low activity and the NO conversion does not exceed 7% in the whole

Table 1
The physicochemical properties of studied catalysts.

Sample	Specific surface area S _{BET} (m ² /g)	t-pole micropore area (m ² /g)	t-pole micropore volume (cm ³ /g)	wt% of Fe	wt% of Cu	Nature of Fe/Cu species
SiBEA	789.7	625.7	0.24	0.019	0.002	–
Fe _{1.0} SiBEA	714.2	537.5	0.21	1.000	–	pseudo-Td Fe ³⁺
Cu _{1.0} SiBEA	764.0	588.2	0.23	–	1.000	pseudo-Td Cu ²⁺
Fe _{1.0} Cu _{1.0} SiBEA	660.6	508.7	0.20	1.000	1.000	framework pseudo-Td Fe ³⁺ and Cu ²⁺
HAIBEA	727.8	565.0	0.22	0.027	0.002	–
Fe _{1.0} HAIBEA	647.1	522.3	0.21	1.000	–	pseudo-Td Fe ³⁺
Cu _{1.0} HAIBEA	635.0	490.8	0.19	–	1.000	mononuclear Cu ²⁺
Fe _{1.0} Cu _{1.0} HAIBEA	616.9	497.2	0.20	1.000	1.000	pseudo-Td Fe ³⁺ and Cu ²⁺

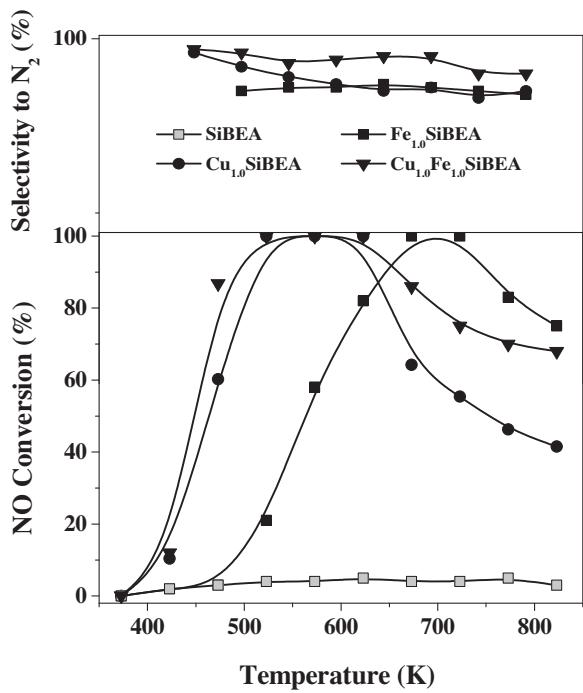


Fig. 4. NO conversion and N₂ selectivity in SCR of NO with NH₃ on SiBEA, Fe_{1.0}SiBEA, Cu_{1.0}SiBEA, Fe_{1.0}Cu_{1.0}SiBEA.

studied temperature range. The NO conversion substantially increases after incorporation of iron in the framework of SiBEA zeolite as pseudo-tetrahedral Fe(III), as shown for Fe_{1.0}SiBEA (Fig. 4). It suggests that pseudo-tetrahedral Fe(III), evidenced by DR UV-vis in Fe_{1.0}SiBEA (Fig. 2), are responsible for high activity of the catalyst in the SCR of NO process, what is in line with earlier studies [18,44,45]. For Fe_{1.0}SiBEA, the NO conversion reaches 100% with the selectivity to N₂ above 90% at temperature higher than 673 K.

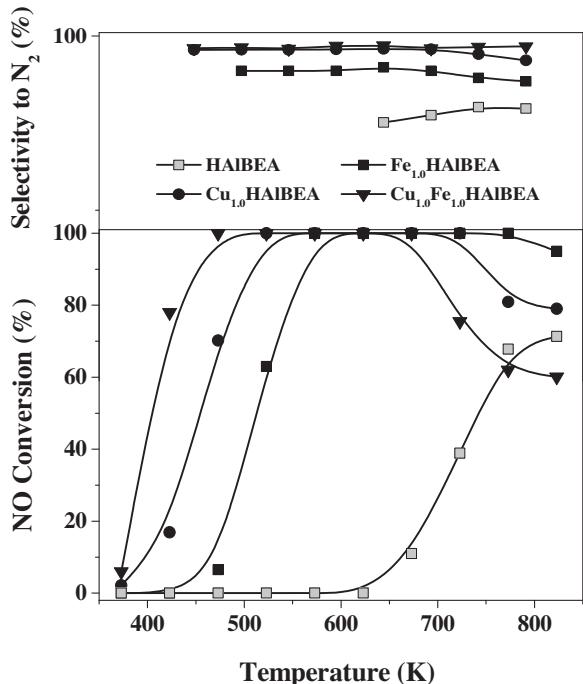


Fig. 5. NO conversion and N₂ selectivity in SCR of NO with NH₃ on HAIBEA, Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA, Fe_{1.0}Cu_{1.0}HAIBEA.

It should be noted that the modification of SiBEA support with copper significantly increases its catalytic activity in the SCR–NO process. The incorporation of Cu into SiBEA leads to its significant catalytic activation (Fig. 4). For the catalyst with 1 wt% of Cu (Cu_{1.0}SiBEA), the reaction starts already at 400 K and NO conversion gradually increases with reaction temperature, as shown in Fig. 4. These results confirm that the presence of copper ions in the framework of zeolite is necessary to promote the activity in SCR of NO, in line with earlier report [19]. The incorporation of Cu into SiBEA as isolated pseudo-tetrahedral Cu(II), evidenced by DR UV-vis and TPR investigations (Figs. 2 and 3), leads to obtain a more active catalyst and the main reaction route is the reduction of NO toward N₂. Indeed, for Cu_{1.0}SiBEA, a substantial increase of the SCR of NO activity is observed with a maximum NO conversion of 100% and selectivity to N₂ above 90% at temperature higher than 473 K. For the Fe_{1.0}SiBEA and Cu_{1.0}SiBEA catalysts a decrease in effectiveness of NO conversion observed in the high temperature region (above 773 K) is related to the side reaction of direct ammonia oxidation by oxygen, present in the reaction mixture. The Fe_{1.0}Cu_{1.0}SiBEA catalyst containing framework pseudo-tetrahedral Fe(III) and Cu(II) (as shown in Fig. 2), presents much better catalytic activity in SCR of NO than the Fe_{1.0}SiBEA and Cu_{1.0}SiBEA catalysts (Fig. 4). Fe_{1.0}Cu_{1.0}SiBEA shows very high NO conversion in a broad temperature range of 473–623 K. It should be noted that a commercial catalysts for this process, based on V₂O₅–TiO₂ oxide system, operate in a significantly narrower temperature range of 523–673 K [46]. Therefore, these preliminary results obtained in our studies, especially for Fe_{1.0}Cu_{1.0}SiBEA are very promising. It should be underline that two-step postsynthesis method applied in this work leads to obtain well-defined catalysts, containing isolated framework Fe (III) and Cu (II) sites that play a major role in SCR–NO reaction, as showed earlier [47,48]. Moreover, for Fe_{1.0}Cu_{1.0}SiBEA the effect of direct ammonia oxidation is less significant than for Cu_{1.0}SiBEA.

Fig. 5 shows the NO conversion as a function of the reaction temperature for all catalysts prepared by conventional wet impregnation of HAIBEA (Fe_{1.0}HAIBEA, Cu_{1.0}HAIBEA and Fe_{1.0}Cu_{1.0}HAIBEA). As typical for SCR–NO reaction, a maximum of NO conversion can be found for all these catalysts in a wide temperature window. First of all, it should be noted that the catalytic activity of zeolite without iron (HAIBEA) is rather good, but only in the high temperature region. The NO conversion exceeds ~70% with the selectivity to N₂ above 80% at temperature higher than 773 K. The modification of HAIBEA support with iron (1 wt%) in the form of pseudo-tetrahedral Fe (III), significantly increases its catalytic activity in the SCR–NO process. For Fe_{1.0}HAIBEA, the NO conversion reaches 100% with selectivity to N₂ above 90% at temperature higher than 553 K. The close reaction performance of the Fe_{1.0}SiBEA and Fe_{1.0}HAIBEA catalysts is in concordance with the similar reducibility of Fe species, deduced from the H₂-TPR experiments (Fig. 3). Results obtained for the sample modified with copper by conventional wet impregnation method are presented in Fig. 5. The Cu_{1.0}HAIBEA catalyst achieved 100% NO conversion at temperature 553 K. In agreement with other authors [5,6], Cu_{1.0}HAIBEA shows maximum activity at lower temperatures (523–723 K) in comparison with Fe_{1.0}HAIBEA (623–783 K). Selectivity to nitrogen, measured for the Cu_{1.0}HAIBEA catalyst, is above 95%. The activity of Fe_{1.0}HAIBEA and Cu_{1.0}HAIBEA zeolites is probably related to the presence in both catalyst simultaneously acidic sites and isolated pseudo-tetrahedral Fe(III) or Cu(II) species, as evidenced by TPR and DR UV-vis investigations (Figs. 2 and 3) [19,46,49–51].

The activity of Fe_{1.0}Cu_{1.0}HAIBEA in the SCR–NO process are presented in Fig. 5. For the Fe_{1.0}Cu_{1.0}HAIBEA catalyst, NO conversion strongly increases with reaction temperatures and NO is completely converted in the reaction mixture in the range of

473–673 K, with selectivity toward N_2 exceeding 97%. The activity of $Fe_{1.0}Cu_{1.0}HAI$ BEA in the reduction of NO with ammonia is influenced by specific iron and copper species, created during modification of HAI BEA zeolite. The framework Cu(II) and Fe(III) present in $Fe_{1.0}Cu_{1.0}HAI$ BEA selectively catalyze the formation of nitrogen without undesirable oxidation of ammonia with oxygen at 773 K and at lower temperature, where its activity and selectivity are stable.

The results obtained for all the catalysts allow comparing their activity in the SCR–NO process. The catalytic activities of all the Fe and/or Cu-containing zeolite catalysts are high, however, it should be noted that $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA are the most active in the low temperature region ($T < 473$ K), while the catalysts containing only 1.0 Fe wt% or 1.0 Cu wt%, (especially $Fe_{1.0}Si$ BEA and $Fe_{1.0}HAI$ BEA), show higher activity at elevated temperatures ($T > 673$ K) (Figs. 4 and 5). As evidenced by DR UV–vis spectroscopy the Fe-containing zeolite catalysts, obtained by conventional wet impregnation, contain pseudo-tetrahedral Fe(III), while the Cu-containing BEA catalysts contain mainly pseudo-tetrahedral Cu(II) species. Thus, it seems that the presence of these species (isolated framework Fe (III) and Cu (II) in pseudo-tetrahedral coordination) in both kinds of the catalysts ($Fe_{1.0}Si$ BEA, $Cu_{1.0}Si$ BEA or $Fe_{1.0}HAI$ BEA, $Cu_{1.0}HAI$ BEA) is responsible for similarity in their high catalytic activity. $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA zeolites effectively operate in the low and medium temperature range (473–673 K). Additionally, the selectivity towards nitrogen, measured for these catalysts, is higher than that observed for the samples modified with iron only ($Fe_{1.0}Si$ BEA, $Fe_{1.0}HAI$ BEA).

It should be underline that the $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA catalysts show a very high NO conversion in a broad temperature range of 473–623 K. The results of the catalytic tests in SCR–NO provided by Metkar et al., [10,11] and other authors [12–16] are characterized by a very similar performance of the dual-layer and dual-brick catalysts. However, it should be noted that the reaction conditions are different in both cases. The $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA samples achieve high NO conversions over a broader temperature range and seems to be strong alternative to the dual-layer or sequential brick, catalysts reported earlier [10–16]. Analysis of the catalytic results of $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA in SCR–NO with NH_3 (Figs. 4 and 5), have shown that postsynthesis as well as wet impregnation procedure allow to obtain the high-performance single-bed catalysts. It is proved that 1 wt% of transition metals, are optimal to incorporate iron and copper in the zeolite structure as pseudo-tetrahedral Fe(III) or Cu(II) that are responsible for high catalytic efficiency in the SCR–NO process. Moreover, the catalytic performance of studied $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA, in contradiction to the dual-layer or dual-brick catalysts [10,11], is not decreased by diffusion limitations.

Although the transition metal ions (Fe, Cu) introduces redox properties into the catalysts and modified their acidic properties [52,53], also the reducibility of the metal ions determines degree of NO conversion over the SCR–NO catalysts [54]. The easier is the reduction of the metal species the higher is its oxidation ability. It is worth to notice that the presence of copper along with iron in the $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA catalysts seems to increase the reducibility of iron species as seen from the TPR profiles (Fig. 3). It is well recognized that in the metal exchanged zeolite catalysts, the reducibility of metal ions determines the extent of the low-temperature NO conversion [55] (Figs. 3, 4 and 5).

However, the easily reducible copper species found in the studied catalysts leads to lower NO conversion at high temperatures due to competing undesired NH_3 oxidation reaction (Figs. 4 and 5). The nitrogen oxide conversion trends in SCR–NO over observed for $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA are in good agreement with earlier literature reports [56,57]. It should be noted that the

presence of Fe and Cu in $Fe_{1.0}Cu_{1.0}Si$ BEA or $Fe_{1.0}Cu_{1.0}HAI$ BEA, shows different reducibility compared with $Fe_{1.0}Si$ BEA, $Fe_{1.0}HAI$ BEA or $Cu_{1.0}Si$ BEA, $Cu_{1.0}HAI$ BEA (Fig. 3A and B). It seems that temperature window of NO conversion can be controlled by adjusting the reducibility of the studied catalysts. If the low-temperature NO conversion is desired, the presence of copper species seems to be important, whereas for the high-temperature conversion the presence of iron species is desired. As discussed above low temperature NO conversion is mostly determined by the ease of reduction of metal ions, and NH_3 storage has inconsiderable role.

It is suggested in many reports [e.g. 58,59,60] that the oxidation of NO to NO_2 is the rate-limiting step for the SCR–NO reaction. Moreover, according to earlier results [59], the Fe^{3+} ions seem to be responsible for increasing the oxidation rate of NO to NO_2 . The earlier published results of NO oxidation by O_2 in the presence of the FeBEA catalysts, obtained by postsynthesis and wet impregnation methods, with framework pseudo-tetrahedral Fe(III) [44] (not shown), proves that the formation of NO_2 is not detected in the studied temperature range (373–823 K). Thus, it seems that the reaction step of NO to NO_2 oxidation in the SCR–NO reaction over these catalysts does not play an important role. According to earlier works [45,50,61] and literature data [60,62], it is likely that the SCR–NO reaction mechanism on FeBEA and CuBEA involves the preliminary adsorption of NO that is oxidized by O_2 forming an adsorbed NO_x species ($x = 2, 3$) bound to a Fe(III) and/or Cu(II) sites. Framework mononuclear Fe(III) and Cu (II) species present in the $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA catalysts could activate ammonia molecule by abstracting hydrogen atom and then forming an N-oxygenated intermediate species [61]. This active intermediate is probably responsible for SCR of NO toward N_2 on the studied catalysts, which is in line with earlier report on Co_xSi BEA [61]. The recent experimental data obtained by us shows that the nitroethane and acetonitrile adsorbed on FeBEA [45] and CoBEA [61] zeolites are very active and selective in the NO conversion to N_2 and seems to be one of the most probable N-oxygenated intermediate species.

There is still discussion related to possible mechanism of SCR of NO including chemisorption and activation of ammonia molecules as well the nature of active N-complexes. For this reason, further studies are undertaken to determine the mechanism and the role of framework Cu and Fe sites in SCR of NO by temperature programmed studies (e.g. NH_3 –TPD–NO, NO–TPD– NH_3 , NH_3 –TPD, NO–TPD, TPSR and FTIR spectroscopy of adsorbed NO and NH_3). Results of these studies will be presented as a continuation of the current studies.

4. Conclusions

Two series of Fe and/or Cu-containing BEA zeolites prepared by two-step postsynthesis and conventional wet impregnation methods were prepared. Transition metals (Cu or Fe) were incorporated into the framework of BEA zeolite as a framework pseudo-tetrahedral Fe(III) or Cu(II), as proved by XRD, DR UV–vis and TPR investigations.

The catalysts containing simultaneously both iron and copper, $Fe_{1.0}Cu_{1.0}Si$ BEA and $Fe_{1.0}Cu_{1.0}HAI$ BEA, have been found to efficiently operate in the SCR–NO process in much broader temperature range comparing to the catalysts modified with only one transition metal (Fe or Cu). Moreover, the selectivity to nitrogen obtained over these catalysts was higher than for the process performed in the presence of the other catalysts. It is proved by the analysis of SCR–NO performance that reducibility of obtained catalysts play an important role in the catalytic process.

The higher activity for the $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{HAI}BEA$ catalyst compared to $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{Si}BEA$ obtained by two-step postsynthesis method, suggested that Fe(III) and Cu (II) species present in the former catalyst, were possibly close to lattice Al, which make them more catalytically active than Fe(III) or Cu (II) species present in siliceous $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{Si}BEA$ zeolite.

Simultaneous presence of Cu and Fe in $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{Si}BEA$ and $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{HAI}BEA$ strongly increases the low temperature NO conversion. Results of SCR-NO with ammonia for $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{Si}BEA$ and $\text{Fe}_{1.0}\text{Cu}_{1.0}\text{HAI}BEA$ revealed that 1 wt% Cu loading is enough to improve the low-temperature NO conversion. It seems that by varying the amount of Cu and Fe in the catalysts the location of the temperature window of efficient NO conversion could be controlled.

Further studies are underway on the $\text{FeCuSi}BEA$ and $\text{FeCuHAI}BEA$ catalysts with a higher Cu and Fe content to verify this phenomenon.

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